

Abstract. We present an analysis of the X-ray light curves of the magnetic cataclysmic variable DP Leo using recently performed XMM–Newton EPIC and archival ROSAT PSPC observations. We determine the eclipse length at X-ray wavelengths to be 235 ± 5 s, slightly longer than at ultra-violet wavelengths, where it lasts 225 s. The implied inclination and mass ratio for an assumed $0.6 M_{\odot}$ white dwarf are $i = 79.7^{\circ}$ and $Q = M_{\text{wd}}/M_2 = 6.7$. We determine a new linear X-ray eclipse and orbital ephemeris which connects the more than 120000 binary cycles covered since 1979. Over the last twenty years, the optical and X-ray bright phases display a continuous shift with respect to the eclipse center by $\sim 2.1^{\circ} \text{ yr}^{-1}$. Over the last 8.5 years the shift of the X-ray bright phase is $\sim 2.5^{\circ} \text{ yr}^{-1}$. We interpret this as evidence of an asynchronously rotating white dwarf although synchronization oscillations cannot be ruled out completely. If the observed phase shift continues, a fundamental rearrangement of the accretion geometry must occur on a time-scale of some ten years. DP Leo is marginally detected at eclipse phase. The upper limit eclipse flux is consistent with an origin on the late-type secondary, $L_X \simeq 2.5 \times 10^{29} \text{ ergs s}^{-1}$ (0.20–7.55 keV), at a distance of 400 pc.

Key words: Stars: binaries: eclipsing – stars: cataclysmic variables – stars:individual: DP Leo – X-rays: stars

An XMM-Newton timing analysis of the eclipsing polar DP Leo

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1. Introduction

DP Leo is one of the strongly magnetic cataclysmic binaries of AM Her type, a so called polar. It was discovered as the first eclipsing polar some 20 years ago as optical counterpart of the EINSTEIN source E1114+182 (Biermann et al. 1985), and continuously observed with from the ground and the space with e.g. HST (Stockman et al. 1994) and ROSAT (Robinson & Cordova 1994, hereafter RC94). It was found to be a two-pole accretor based on the detection of cyclotron emission lines in field strengths of 30.5 MG and 59 MG, respectively (Cropper & Wickramasinghe 1993). A thorough timing study by Robinson & Cordova (1994) using ROSAT X-ray data combined with earlier optical data revealed evidence for an asynchronous rotation of the white dwarf in the system. Asynchronous polars form a very small subgroup of all polars. There are four out of currently known 65 systems which show a small degree of asynchronism of typically about 1% (Campbell & Schwope 1999). With an extra spin of the white dwarf in DP Leo of about 2° – 2.5° per year, the degree of asynchronism is seemingly much smaller than in the other four objects. However, the earlier results are based on a mixture of optical and X-ray data with not necessarily common origin on the white dwarf.

DP Leo was chosen as Calibration/Performance Verification target of XMM-Newton and was observed with all three X-ray telescopes in Nov. 2000. The spectrum derived from these observations was recently published by Ramsay et al. (2001). Using a multi-temperature model of the post-shock flow, they found evidence of a very massive white dwarf in excess of $1 M_\odot$. In order to address the question of asynchronism in DP Leo based on X-ray data alone, we performed a timing analysis of the new XMM-data in combination with archival ROSAT observations (one published by Robinson & Cordova, a second one unpublished, Sect. 2). For proper measurement of the eclipse parameters we used segmented data, where individual segments were determined with a Bayesian change point detection method (Sect. 2.3). Our main results are presented in Sect. 3, where the eclipse parameters, an up-

dated eclipse ephemeris and the accretion geometry are discussed. The question whether there is a positive detection of the secondary at X-ray wavelengths in the eclipse is discussed in Sect. 3.5.

2. Observations and Data reduction

2.1. XMM-Newton EPIC

DP Leo was observed using XMM-Newton on 22 of November 2000 for a net exposure time of 19949 s. DP Leo was detected in all three EPIC detectors (Turner et al. 2001, Strüder et al. 2001). The thin filter was used and the CCDs were read out in full window mode.

Before extracting source photons, the data were processed using the current release of the XMM-Newton Science Analysis System (version 5.1). Standard procedures of data screening (creation of an image and a background light curve) revealed time intervals with enhanced particle background. These intervals were excluded from the subsequent timing analysis using an approach described below (See Sect. 2.3). This reduces the accepted exposure time to 15827 sec with the EPIC-PN detector. The observations were performed without any interruption, i.e. full phase-coverage of the $P_{\text{orb}} = 5388$ s binary was achieved with an average exposure of ~ 150 s per 0.01 phase unit.

2.2. ROSAT PSPC

The field of DP Leo was also observed with the ROSAT PSPC on May 30, 1992 (ROR 300169, PI: Cordova) and on May 30, 1993 (ROR 600263, PI: Petre) for a net exposure time of 8580 s and 23169 s, correspondingly. Results of the 1992 observations were presented by Robinson & Cordova (1994), the results of the much more extended observations of 1993 are unpublished.

Although the net exposure time of the two ROSAT observations was larger than the binary period, in **neither case was complete phase coverage achieved due to the close proximity of the periods of the satellite and of the binary.**

There are further X-ray observations reported by Biermann et al. (1985), and Schaaf et al. (1987), respectively,

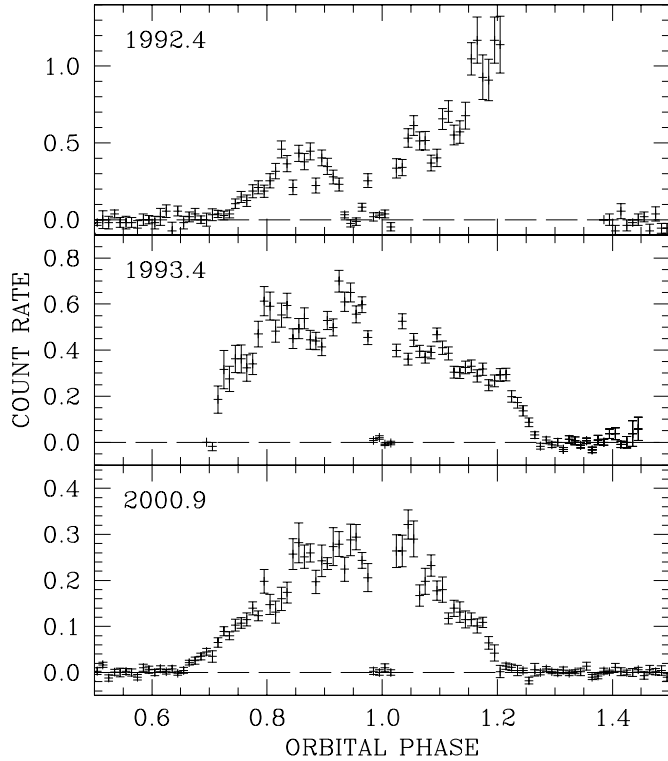


Fig. 1. Phase-averaged X-ray light curves of the ROSAT and the XMM-Newton observations. Phase bins have a size of 0.01 phase units of the $P_{\text{orb}} = 5388\text{s}$ binary.

with the EINSTEIN and EXOSAT satellites. We make use of the timing of the X-ray eclipses detected with Einstein, the EXOSAT data have a too low count-rate and are not used further in this paper.

2.3. Timing analysis with a Bayesian change point detection method

In order to study the abrupt changes of the X-ray count rate particularly at eclipse ingress and egress we performed a timing analysis of the datasets using a Bayesian change point detection method¹ developed by Scargle (1998, 2000). This method is well suited for a statistical examination when the arrival times of individual X-ray photons are registered (see Hambaryan et al. 1999). It is superior to methods which work on binned data, since it requires no a priori knowledge of the relevant time-scale of the structure which will be investigated.

The method is applicable to data that are known to originate from a nearly ideal Poisson process, i.e. a class of independent, identically distributed processes, having zero lengths of dead time. The data gathered in XMM-Newton

EPIC-PN and ROSAT PSPC observations allow the measurement of arrival times of individual X-ray photons with a resolution of 73.3 ms and 0.1 ms, respectively, a resolution much smaller than the ingress and egress time scale which is of the order of seconds. The EPIC-MOS data cannot be used for the study of the eclipse length, since it provides a resolution of only 2.6 s.

Scargle’s (1998, 2000) method decomposes a given set of photon counting data into Bayesian blocks with piecewise constant count-rate according to Poisson statistics. Bayesian blocks are built by a Cell Coalescence algorithm (Scargle 2000), which begins with a fine-grained segmentation. It uses a Voronoi tessellation² of data points, where neighboring cells are merged if allowed by the corresponding marginal likelihoods (see Scargle 2000).

We repeat here the essential parts of the method, expanding upon particular modifications of the original method as used in the present application. Assume that during a continuous observational interval of length T , consisting of m discrete moments in time (spacecraft’s “clock tick”), a set of photon arrival times $D(t_i, t_{i+1}, \dots, t_{i+n})$ is registered. Suppose now that we want to use these data to compare two competing hypotheses. The first hypothesis is that the data are generated from a constant rate Poisson process (model M_1) and the second one from two-rate Poisson process (model M_2). Evidently, model M_1 is described by only one parameter θ (the count rate) of the one rate Poisson process while the model M_2 is described by parameters θ_1 , θ_2 and τ . The parameter τ is the time when the Poisson process switches from θ_1 to θ_2 during the total time T of observation, which thus is divided in intervals T_1 and T_2 .

By taking as a background information (I) the proposition that one of the models under consideration is true and by using Bayes’ theorem we can calculate the posterior probability of each model by (the probability that M_k ($k = 1, 2$) is the correct model, see, e.g., Jaynes 1997)

$$Pr(M_k|D, I) = \frac{Pr(D|M_k, I)}{Pr(D|I)} Pr(M_k|I) \quad (1)$$

where $Pr(D|M_k, I)$ is the (marginal) probability of the data assuming model M_k , and $Pr(M_k|I)$ is the prior probability of model M_k ($k = 1, 2$). The term in the denominator is a normalization constant, and we may eliminate it by calculating the ratio of the posterior probabilities instead of the probabilities directly. Indeed, the extent to which the data support model M_2 over M_1 is measured by the

¹ In general terms, the change-point methodology deals with sets of sequentially ordered observations (as in time) and determines whether the fundamental mechanism generating the observations has changed during the time the data have been gathered (see, e.g. Csörgő & Horváth, 1997).

² The Voronoi cell for a data point consists of all the space closer to that point than to any other data point.

ratio of their posterior probabilities and is called the posterior odds ratio

$$O_{21} \equiv \frac{Pr(M_2|D, I)}{Pr(M_1|D, I)} = \left[\frac{Pr(D|M_2, I)}{Pr(D|M_1, I)} \right] \left[\frac{Pr(M_2|I)}{Pr(M_1|I)} \right]. \quad (2)$$

The first factor on the right-hand side of Eq. (2) is the ratio of the *integrated* or *global* likelihoods of the two models and is called the *Bayes factor* for M_2 against M_1 , denoted by B_{21} . The global likelihood for each model can be evaluated by integrating over nuisance parameters and the final result for discrete Poisson events can be represented by (see, for details, Scargle 1998, 2000, Hambaryan et al. 1999)

$$B_{21} = \frac{1}{B(n+1, m-n+1)} \sum B(n_1+1, m_1-n_1+1) \quad (3)$$

$$\times B(n_2+1, m_2-n_2+1) \Delta\tau,$$

where B is the *beta function*, n_j and m_j , ($j = 1, 2$), respectively are the number of recorded photons and the number of “clock ticks” in the observation intervals of lengths T_1 and T_2 . $\Delta\tau$ is the time interval between successive photons, and the sum is over the photons’ index.

The second factor on the right-hand side of Eq. (2) is the prior odds ratio, which will often be equal to 1 (see below), representing the absence of an *a priori* preference for either model.

It follows that the Bayes factor is equal to the posterior odds when the prior odds is equal to 1. When $B_{21} > 1$, the data favor M_2 over M_1 , and when $B_{21} < 1$ the data favor M_1 .

If we have calculated the odds ratio O_{21} , in favor of model M_2 over M_1 , we can find the probability for model M_2 by inverting Eq. (2), giving

$$Pr(M_2|D, I) = \frac{O_{21}}{1 + O_{21}}. \quad (4)$$

Applying this approach to the observational data set, Scargle’s (1998, 2000) method returns an array of rates, $(\theta_1, \theta_2, \dots, \theta_{cp})$, and a set of so called “change points” $(\tau_1, \tau_2, \dots, \tau_{cp-1})$, giving the times when an abrupt change in the rate is determined, i.e. a significant variation. This is the most probable partitioning of the observational interval into blocks during which the photon arrival rate displayed no statistically significant variations.

We determined the timing accuracy of these change points through simulations. We generated 1000 data sets (photon arrival times) with one change point each. The data in the two segments obeyed Poisson statistics. Each simulated data set had approximately the same characteristics as the observed data in terms of number of registered counts, spanned time, characteristic time scales of expected variations, and was analyzed exactly in the same way. The standard deviation of the distribution of change points was found to be $\Delta\tau_{cp} = \pm(2-3)$ s, if phase-folded

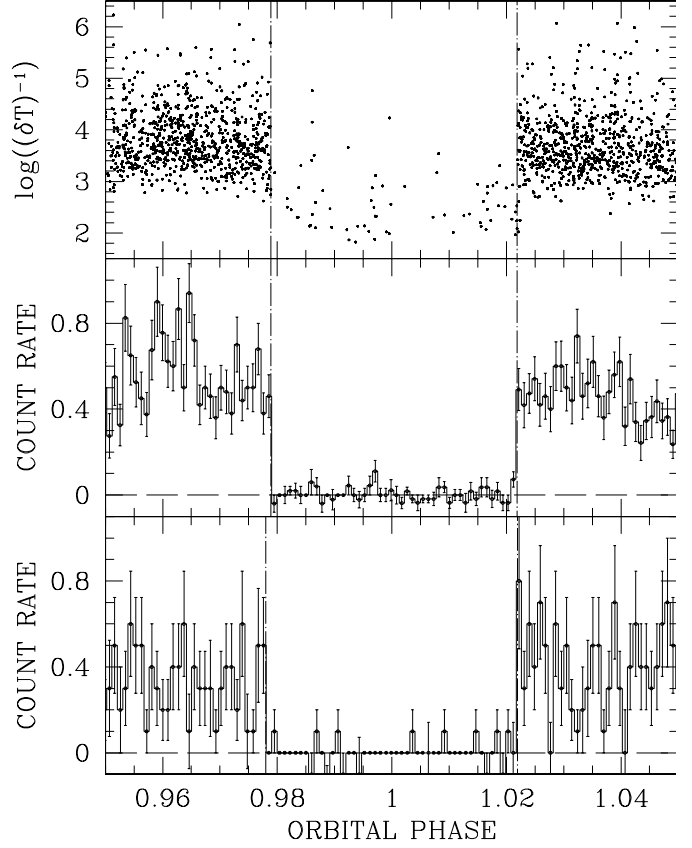


Fig. 2. Determination of the eclipse length for the ROSAT 1993 (upper two panels) and the XMM-Newton observations (lower panel) of DP Leo. The upper panel shows the distribution of the reciprocals of the time intervals between neighbouring photons, the two lower panels binned X-ray light curves (bin size 5 sec). Vertical lines indicate the change points in the Poisson process, the space between them is our measured eclipse length.

data are used. The uncertainty was larger, when data in original time sequence were used due to the smaller total number of photons involved. We adopted an uncertainty of 2.5 s for the observationally determined change points which were used to derive the eclipse length.

In Fig. 2 we visualize the outcome of the process for the ROSAT observations performed in 1993 and for the XMM-Newton observations (EPIC-PN data only). The top panel shows the distribution of the reciprocal of the time interval between neighbouring photons (1993 data), in the two lower panels the X-ray light curves binned in intervals of 5 sec are plotted. The change points determined by our method are indicated by vertical lines.

2.3.1. XMM-Newton EPIC PN

As a first step, we applied the change point detection method to a background region free of any X-ray source.

Table 1. Features of the X-ray light curve derived from ROSAT and XMM–Newton observations of DP Leo. For a given epoch and instrument we list the mean count rate in the phase interval 0.80–0.90, the length of the eclipse Δt_{ecl} , the phase of the center of the bright phase interval ϕ_C , and the length of the bright phase $\Delta\phi_B$. **The center of the bright phase is interpreted as accretion spot longitude.**

| Epoch | Mission/Det | CR [s ⁻¹] | Δt_{ecl} [s] | ϕ_C | $\Delta\phi_B$ |
|--------|-----------------|--------------------------|--------------------------------|-------------------|----------------|
| 1992.4 | ROSAT/PSPC | 0.35 | 237 ± 5 | 0.006 ± 0.006 | – |
| 1993.4 | ROSAT/PSPC | 0.50 | 233 ± 5 | 0.013 ± 0.006 | 0.57 |
| 2000.9 | XMM–Newton/EPIC | 0.25 | 237 ± 5 | 0.067 ± 0.006 | 0.57 |

This allowed us to determine time intervals where the background showed no significant variation. These were regarded as good time intervals and further used for the timing analysis of DP Leo.

We extracted ~ 3180 EPIC-PN photon events from the source, whose arrival times were corrected to the solar system barycenter using the “barycen” task, as implemented in SAS version 5.1.

We used phase-folded data and data in original time sequence in order to determine different quantities. The length of the bright phase and the eclipse length were measured in phase-folded data, the times of individual eclipses (for a period update) were measured in original time sequence.

The mean bright-phase count-rate, the eclipse length, bright phase center and length of bright phase are listed in Tab. 1, whereas the times of mid-eclipse of the individual eclipses are listed in Tab. 2. The times given there are barycentric Julian ephemeris days, i.e. they take into account the 14 leap-seconds introduced between the first and the last data point. Since leap-seconds were omitted by seemingly all authors in the past (**all timings in the literature are given in HJD only**), we computed for all eclipse times we found in the literature the leap-second correction and include those times in the table for consistency and future work.

2.3.2. ROSAT PSPC

We also performed a timing analysis of the ROSAT PSPC observations. In both cases we used a circular region with $30''$ radius to extract source photons. In total 2705 and 8385 source counts were extracted, respectively. The radius chosen encompasses 85% of the events in the ROSAT point spread function. Photon arrival times were corrected to the solar barycenter, as implemented in the Extended Scientific Analysis Software System (Zimmerman et al. 1998).

These data were treated in the same manner as the XMM–Newton data and the corresponding results are also listed in Tabs. 1 and 2.

3. Results and discussion

3.1. X-ray light curves and mean spectra of DP Leo

The phase-averaged X-ray light curves of the two ROSAT and the XMM–Newton observations (summed signal from all three cameras) are shown in Fig. 1. At all occasions the source showed a pronounced on/off behavior with the eclipse roughly centered on the X-ray bright phase. The eclipse was covered 3 times in 1992, 8 times in 1993, and 2 times in the PN-observation (good time intervals only, one eclipse was excluded from the analysis due to high particle background).

In the 1992 observation the source showed a pronounced flare at phase 0.2. The end of the bright phase was not covered, the length of the bright phase, however, was inferred by RC94 from contemporaneous optical photometry. A pre-eclipse dip, likely due to the intervening accretion stream occurred centered at phase 0.94. Interestingly, this feature was never observed again, indicating a re-arrangement of the accretion geometry.

The 1993 observation covered the X-ray bright phase completely (although marginally at the start) thus allowing to measure the length of the bright phase from X-ray data alone. The source displayed similar brightness during the two ROSAT observations. The eclipse appeared centered on the bright phase.

In 2000, the shape of the X-ray bright phase appeared almost unchanged compared to the 1993 observation. The eclipse now was clearly off-centered with respect to the bright phase. The rise to the bright phase was somewhat less steep than the fall. Compared with the earlier ROSAT observations, DP Leo appeared fainter in the center of the bright phase. According to Ramsay et al. (2001) and Pandel et al. (2001) DP Leo was in a state of intermediate accretion at the time of the XMM–Newton observations, whereas it was in a high state at the time of the ROSAT observations. The comparison of published results combined with our own analysis shows that the situation might be different.

For the PSPC observations of 1992, RC94 derive a bolometric blackbody luminosity for an assumed distance of 260 pc of $L_{\text{bb,bol}} = \kappa\pi F_{\text{bb}} = 1.4^{+7.1}_{-0.3} \times 10^{31} \text{ erg s}^{-1}$. Scaling to the more likely distance of 400 pc gives $L_{\text{bb,bol}} = 3.3 \times 10^{31} \text{ erg s}^{-1}$. RC94 used a geometry factor $\kappa = 2$. Ramsay et al. (2001) used $\kappa = \sec(i - \beta) = \sec(80^\circ - 100^\circ) = 1.06$ and a distance of 400 pc and derive $1.5 \times$

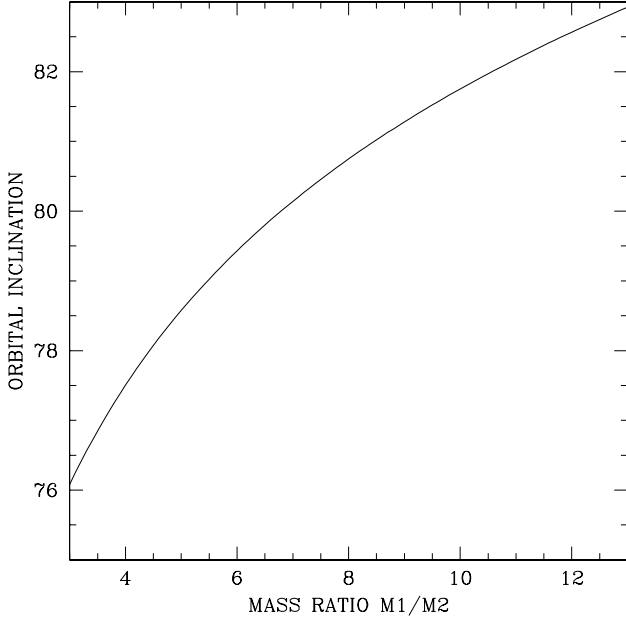


Fig. 3. Relation between mass ratio and inclination for an eclipse length of 225 s.

$10^{31} \text{ erg s}^{-1}$ with the EPIC MOS detectors, more than twice that value with the EPIC PN detector. Within the accuracy of the measurements and scaled to the same geometry factors the luminosities of the soft components at both epochs agree with each other.

Contrary to the PSPC observations in 1992, there is a clear detection of DP Leo above 0.5 keV in the PSPC observation performed in 1993, which allows fitting of a two-component spectrum. With the spectral resolution provided by the ROSAT PSPC, the spectrum is well reflected by a combination of a black-body and a bremsstrahlung component. We fixed the bremsstrahlung temperature at the typical temperature of $kT_{\text{br}} = 15 \text{ keV}$. The bolometric flux in the bremsstrahlung component thus derived was $F_{\text{br},93} = 2.9 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$. Application of the same simple model to the EPIC PN data, and adding a Gaussian for the iron line at 6.7 keV, gives a fitted temperature of $kT_{\text{br}} = 11 \pm 6 \text{ keV}$ and a bolometric flux of $F_{\text{br},00} = 2.4 \times 10^{-13} \text{ erg cm}^{-2} \text{ s}^{-1}$, which again is not in contradiction to the former ROSAT measurements. We conclude that the X-ray observations do not indicate an obvious change of the mass accretion rate between the three epochs.

3.2. Timing of the X-ray eclipse

Application of our method to the data of DP Leo allowed an accurate determination of the eclipse length at X-ray wavelengths. The measurements at all three epochs agree with each other within the claimed accuracy, **ranging from 233 s to 237 s with a 5 second accuracy**

Table 2. Times of mid-eclipse of all eclipses measured including new ROSAT and XMM-Newton data. Individual times are leap-second corrected times at the solar system barycenter (BJED: barycentric Julian ephemeris day).

| Epoch | Cycle | BJED -2400000 | δT (sec) | Type ⁽¹⁾ |
|--------|--------|------------------|---------------------|---------------------|
| 1979.9 | -73099 | 44214.55325 | 15 | X |
| 1979.9 | -73098 | 44214.61562 | 15 | X |
| 1979.9 | -73097 | 44214.67798 | 15 | X |
| 1982.0 | -61017 | 44968.02309 | 100 | O |
| 1982.0 | -61002 | 44968.95712 | 100 | O |
| 1982.0 | -61001 | 44969.01962 | 100 | O |
| 1982.0 | -60841 | 44978.99755 | 100 | O |
| 1982.1 | -60602 | 44993.90078 | 60 | O |
| 1982.1 | -60601 | 44993.96328 | 60 | O |
| 1982.1 | -60600 | 44994.02642 | 60 | O |
| 1982.1 | -60169 | 45020.90513 | 20 | O |
| 1982.1 | -60153 | 45021.90292 | 20 | O |
| 1982.2 | -60106 | 45024.83386 | 60 | O |
| 1984.1 | -48767 | 45731.96640 | 30 | O |
| 1984.2 | -48256 | 45763.83373 | 5 | O |
| 1984.4 | -46796 | 45854.88280 | 100 | X |
| 1985.0 | -43588 | 46054.94231 | 100 | X |
| 1985.1 | -43075 | 46086.93565 | 3 | O |
| 1985.1 | -43074 | 46086.99796 | 3 | O |
| 1991.8 | -3410 | 48560.55789 | 4 | UV |
| 1992.4 | 0 | 48773.21509 | 5 | X |
| 1992.4 | 16 | 48774.21293 | 5 | X |
| 1993.4 | 5848 | 49137.91294 | 5 | X |
| 1993.4 | 5945 | 49143.96214 | 5 | X |
| 1993.4 | 5946 | 49144.02438 | 5 | X |
| 1993.4 | 5947 | 49144.08689 | 5 | X |
| 1993.4 | 5961 | 49144.96005 | 5 | X |
| 1993.4 | 5962 | 49145.02235 | 5 | X |
| 1993.4 | 5963 | 49145.08454 | 5 | X |
| 1993.4 | 5964 | 49145.14711 | 5 | X |
| 2000.9 | 49670 | 51870.77761 | 5 | X |
| 2000.9 | 49672 | 51870.90237 | 5 | X |

⁽¹⁾ X = X-ray; O = optical; UV = UV

(see Tab. 1). The average eclipse length is somewhat longer than that deduced from HST/FOS observations. Figure 5 of the paper by Stockman et al. (1994) implies that the eclipse length at ultraviolet wavelengths is about 225 s (measured at half intensity). The difference in the length of the ultraviolet and X-ray eclipses is due to the fact, that the source of X-ray emission is closer to the secondary star than the source of the ultraviolet radiation. The former originates from the hot accretion spot while the latter has contributions from the whole surface of the white dwarf. We regard the eclipse length determined in ultraviolet data as relevant for the mass determination. Using the relation between eclipse length (in phase units), inclination and mass ratio given by Chanan et al. (1976) and a eclipse length of 0.0209 phase units (225 s), the rela-

tion between mass ratio and inclination as shown in Fig. 3 results.

At the given period, the mass-radius relation for late-type stars by Caillault & Patterson (1990) predicts a secondary star with mass of only $0.09 M_{\odot}$. Assuming a typical white dwarf with $M_{\text{wd}} = 0.6 M_{\odot}$, the mass ratio is $Q = M_{\text{wd}}/M_2 = 6.7$ and the implied orbital inclination $i = 80^\circ$ (cf. Bailey et al. 1993). Ramsay et al. (2001) argued for a high mass white dwarf near the Chandrasekhar limit on the basis of their spectral model applied to the XMM–Newton data. This would imply a slightly higher inclination of $i > 82^\circ$. **However, the comparison of white dwarf masses based on their model with dynamically determined masses in the well-studied polars QQ Vul ($M_{\text{dyn}} = 0.54 M_{\odot}$ vs. $M_{\text{Xfit}} = 1.30 M_{\odot}$; Catalán et al. 1999, Cropper et al. 1999) and AM Her ($M_{\text{dyn}} = 0.45 M_{\odot}$ vs. $M_{\text{Xfit}} = 0.74 M_{\odot}$; Schwarz et al. 2001, Ramsay et al. 2000) shows that the X-ray spectralmodel tends to predict a too high mass for the white dwarf. A high mass white dwarf seems unlikely to us given the good fit shown by Bailey et al. (1993) to their optical eclipse light curve. A massive white dwarf would have less than half the radius of the $0.7 M_{\odot}$ white dwarf used by Bailey et al. and would not give a comparably good fit. We use, therefore, as a baseline for our further analysis the standard value $M_{\text{wd}} = 0.6 M_{\odot}$.**

The new determination of the eclipse length has a much higher accuracy than that by RC94, who give 216 ± 18 s and demonstrates the benefit of the Bayesian change point method. RC94 derive an upper limit of ~ 22 s on the length of the eclipse ingress/egress phase. **The binned eclipse light curves of Fig. 2 clearly show, that eclipse ingress and egress lasts much shorter than 22 sec in the observations performed in 1993 and 2000 but the count rate is not sufficient to resolve ingress and egress. We therefore cannot derive strong constraints on the lateral extent of the X-ray emission region. For comparison, in UZ For and HU Aqr where the egress phases could be resolved by EUVE and ROSAT observations, respectively, these features last only about 1.3 s (Warren et al. 1995, Schwope et al. 2001a), corresponding to a full opening angle of the X-ray emission region on the white dwarf of only 3° .**

We proceed by updating the eclipse ephemeris of DP Leo by using X-ray data alone. We disregard optical data for this purpose since it is shown for other polars (e.g. in HU Aqr, Schwope et al. 2001b), that the optical and X-ray emitting regions might be disjunct. This could result in a shift of the X-ray with respect to the optical eclipse by several seconds and would corrupt the period determination. A linear regression to the eclipse times measured with EINSTEIN, ROSAT, and XMM–Newton yields

$$\text{BJED}_{\text{X,ecl}} = T_{0,\text{ecl}} + E \times P_{\text{ecl}}$$

$$\text{BJED}_{\text{X,ecl}} = 2448773.21503(2) + E \times 0.0623628471(5)$$

for the barycentrically and leap-second corrected time of the X-ray eclipse center. This is not to be mixed up with the orbital period of the binary system, since we are measuring the eclipse of a small structure on the white dwarf surface which obviously is not fixed in the binary system. Our determination of P_{ecl} is consistent with that of RC94 only at the 2.5σ level with our period being longer. One reason for the slight inconsistency could be the omission of leap seconds by RC94, another the use of different types of input data, X-ray and optical data by RC94, X-ray data alone by us.

3.3. Spot geometry and true phase zero

The derivation of the true binary period of the system needs independent information about the eclipse of the white dwarf center (not the spot on it!). There is one direct measurement in the literature (Stockman et al. 1994) available to us based on HST/FOS measurements. One can correct from the observed X-ray mid-eclipse times to the times of mid-eclipse of the white dwarf. We did this for the eclipse data which entered the determination of P_{ecl} above. This correction is based on the following parameters: $i = 79.65^\circ$, $Q = 6.7$, $M_{\text{wd}} = 0.6$, mass-radius relations for the white dwarf and the secondary by Nauenberg (1972) and Caillault & Patterson (1990), spot latitude 100° , spot longitude at the different epochs as listed in Tab. 1, the longitude at the time of the EINSTEIN observation was -22° . Usage of these parameters gives the correct eclipse length and length of the bright phase, if a height of the emission region of $0.02 R_{\text{wd}}$ is taken into account. The assumed height is in accord with other polars (e.g. Schwope et al. 2001a). The small corrections to the eclipse times as listed in the above table are $+5.7, -0.5, -1.2, -6.2$ s for the EINSTEIN, ROSAT 1992, ROSAT 1993, and the XMM–Newton observations, respectively. A linear regression to the corrected timings including the HST measurement gives the ephemeris of inferior conjunction of the secondary

$$\text{BJED}_{\text{XUV,orb}} = T_{0,\text{orb}} + E \times P_{\text{orb}}$$

$$\text{BJED}_{\text{XUV,orb}} = 2448773.21503(2) + E \times 0.0623628460(6).$$

The binary period P_{orb} is slightly shorter than P_{ecl} , as expected. Both zero points, $T_{0,\text{orb}}$ and $T_{0,\text{ecl}}$, agree with each other, since the spot was at about longitude zero at the epoch, when our cycle counting starts. The introduction of a quadratic term, as discussed by RC94, gives a bad fit to the data with an $(O - C)$ time of about one minute at the epoch of the XMM–Newton observations and is therefore ruled out.

3.4. Spot longitude variations

The large shift of the bright phase with respect to the eclipse is interesting as such. RC94 noticed that since the early observations in 1980 the bright phase was continuously shifted from negative longitudes to about zero lon-

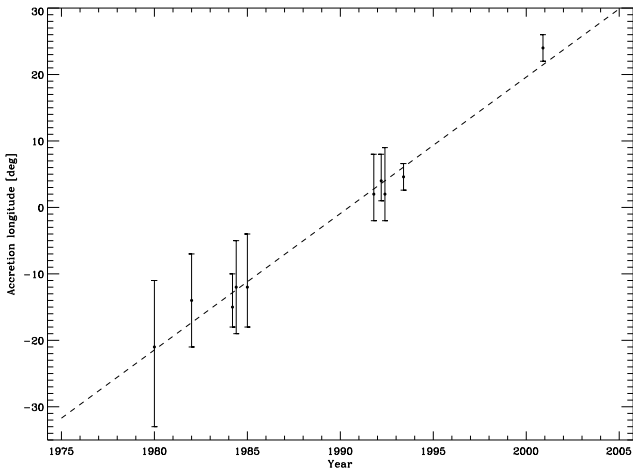


Fig. 4. Accretion spot longitude variations as a function of time. The last two data points are from this work, the other points are from RC94. The dashed line is a linear fit to all data.

gitude in 1992 and they deduced a yearly shift of the spot longitude of 2.05° . The data collected in Tab. 1 imply that this shift might become even larger, $\Delta\chi = 2.5^\circ \text{ yr}^{-1}$. Fig. 4 shows the synopsis of all the bright phase center (spot longitude) measurements. The phase shift is continuous and monotonic over the last 20 years. The spot started at negative longitudes, i.e. in the half-sphere away from the ballistic accretion stream and now approaches the more typical (natural ?) location at about 30° (see Cropper (1988) for a compilation of accretion spot longitudes).

Spot longitude variations can be caused by changes of the mass accretion rate, by synchronization oscillations or by an asynchronously rotating white dwarf. Accretion rate changes would not imply a monotonic phase shift, they would imply a positive spot longitude at high accretion rate and a smaller longitude at low accretion rate. Since the accretion rate most probably did not change considerably between the ROSAT and the XMM-Newton observations, spot longitude are difficult to explain this way.

Synchronization oscillations are predicted to occur once a locked state between the white dwarf and the secondary star is reached (Campbell 1989, King & Whitehurst 1991). So far no measurement could be performed in order to test the theory, the relevant time-scales and the amplitudes of these oscillations. The predicted period of small oscillations about the locked state is $P_{\text{osc}} \simeq 25 \text{ yr}$ (Campbell & Schwope 1999), i.e. of the order of the time base covered meanwhile by the observations. There is no indication of a reversal of the spot longitude migration implied by an oscillation scenario. We therefore tend to favor the scenario of a dis-locked white dwarf and thus add DP Leo to the small sub-class of asynchronous polars with so far four members only (Campbell & Schwope

1999). If our assignment is correct, DP Leo is different from the other systems in this sub-class showing a much smaller degree of asynchronism. RC94 already estimated the deviation $(P_{\text{orb}} - P_{\text{rot}})/P_{\text{orb}} \simeq 10^{-6}$, whereas the absolute of this quantity in the other four is $\sim 10^{-2}$. We note that we cannot properly measure the spin period of the white dwarf in DP Leo, since the accretion spot is not fixed in the magnetic coordinate system of the white dwarf. Should the degree of asynchronism be of the order as derived here, a fundamental re-arrangement in terms of a pole-switch must occur sometimes in the not too far future.

3.5. X-ray emission from the secondary star?

We searched the XMM-Newton data for photons in the eclipse, which would be ascribed to the putative active secondary star. Omitting the first and last 10 seconds of the eclipse the total exposure time in eclipse investigated by us was 1436 s and included 6 eclipses (three cameras) in good time intervals. In the source-plus-background region 29 photons were registered, while in the neighboring background region only 18 photons were registered.

In order to estimate the likely count rate only from the source, we employed a Bayesian estimate using a method described by Loredó (1992), which is applicable to a dataset with low number of counts having a Poisson distribution.

The most probable value of the count rate was $0.0075 \text{ cts s}^{-1}$ taken from the evaluated full Bayesian probability distribution function. A Bayesian credible region (a 'posterior bubble') is $0.0030 - 0.0120 \text{ cts s}^{-1}$ in a 68% (1σ) confidence interval. The 99.73% (3σ) credible region gives a value $0.0000 - 0.0212 \text{ cts s}^{-1}$, consistent with zero. We regard our finding as uncertain marginal detection of the secondary in X-rays.

With the nominal count rate the luminosity of the secondary is

$$L_X = 2.5 \times 10^{29} (D/400 \text{ pc})^2 \text{ ergs s}^{-1} \text{ (0.20 - 7.55 keV)}.$$

For this estimate we used a count to flux conversion factor $\sim 1.6 \times 10^{-12} \text{ ergs cm}^{-2} \text{ s}^{-1} \text{ cts}^{-1}$, adopted from a spectral study of one of the M5 type stars available in the XMM-Newton Lockman Hole data (see also Hasinger et al 2001).

This estimate is consistent with coronal emission of late type stars from the solar vicinity (Hünsch et al. 1999).

4. Summary and conclusion

We have analyzed XMM-Newton observations of the eclipsing polar DP Leo performed in the Calibration/Performance Verification phase in November 2000 in parallel with former ROSAT-SPSC observations. The center of the bright phase indicates a accretion spot longitude of $\sim 24^\circ$ at the epoch of the XMM-Newton observations. Compared to former observations, it was shifted towards

later phase, a continuation of a trend over the last 20 years. This finding is regarded as indicative of an asynchronous white dwarf, although synchronization oscillations around an equilibrium position cannot be ruled out. The difference between the binary period, P_{orb} , and the white dwarf rotation period, P_{rot} , is small $(P_{\text{orb}} - P_{\text{rot}})/P_{\text{orb}} \simeq 10^{-6}$, 4 orders of magnitude smaller than for any other of the presently known four asynchronous polars. We have derived accurate ephemerides for the center of the X-ray eclipse and inferior conjunction of the secondary in DP Leo, corrected for the leap seconds introduced between 1979.9 and 2000.9 and reduced to the solar system barycenter. This can be used as reference for further studies of the evolution of the period of the binary and of the spin period of the white dwarf. Although we were able to correct the observed X-ray eclipse times to true binary phase zero through eclipse modeling, a direct determination of the conjunction is highly desirable. This would allow the proper measurement of a possible spin-up or spin-down of the white dwarf in DP Leo. The only way to achieve this in DP Leo is through high-speed photometry (preferentially in the ultra-violet), thus revealing the white dwarf. The determination of conjunction of the secondary star be e.g. a spectral tracing seems to be impossible due to the faintness of this low-mass star. It was not yet detected spectroscopically, Bailey et al. (1993) photometrically derive an R -band magnitude of $21^{\text{m}}8$.

It is interesting to note, that only the spot longitude displays large-scale shifts but not the latitude. A shift in latitude would result in a different length of the bright phase. No such effect is observed, the length of the bright phase is always ~ 0.57 phase units. Should an oscillation scenario be applicable to DP Leo, the non-observed latitudinal shift is an important extra datum for theory. The model of e.g. King & Whitehurst (1991) predicts a large-amplitude out-of-plane oscillation (60° or more).

Our detection of the secondary in X-rays is marginal, the derived flux and luminosity are in agreement with that of single M-stars, which rotate much slower. However, a secure statement about the X-ray flux of the secondary star requires a much deeper exposure.

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